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OPTOELECTRONIC TECHNOLOGY CONSORTIUM

Quarterly Technical Report No.3
January 1 to March 31, 1992
Honeywell, Inc.

1.0 Introduction.

The Optoelectronic Technology Consortium has been established to position U.S. industry as the world leader in optical interconnect technology by developing, fabricating, integrating and demonstrating the producibility of optoelectronic components for high-density/high-data-rate processors and accelerating the insertion of this technology into military and commercial applications. This objective will be accomplished by a program focused in three areas.

> Demonstrated performance: OETC will demonstrate an aggregate data transfer rate of 16 Gb/s between single transmitter and receiver packages, as well as the expandability of this technology by combining four links in parallel to achieve a 64 Gb/s link.
>
> Accelerated development: By collaborating during the precompetitive technology development stage, OETC will advance the development of optical components and produce links for a multiboard processor testbed demonstration.
>
> Producibility: OETC's technology will achieve this performance by using components that are affordable, and reliable, with a line BER$<10^{-15}$ and MTTF$>10^6$ hours.

Under the OETC program Honeywell will develop packaged AlGaAs arrays of waveguide modulators and polymer based, high density, parallel optical backplane technology compatible with low-cost manufacturability.

The packaged AlGaAs modulator arrays will consist of a single fiber input, a 1x4 fanout circuit, four waveguide modulators, and four fiber outputs, all mounted on a ceramic header. The primary benefits to this approach are enhanced system reliability, particularly at high temperatures, and a device design that is highly producible due to the inherent process tolerance. Combined with the demonstrated high density of these devices when fabricated in arrays, this allows the development of compact and reliable transmitter components.

The objective of the polyimide backplane development effort is to demonstrate a practical high density (>20 lines or channels per mm) parallel optical backplane facilitating (bandwidth x length/power) interconnect figures of merit between one and two orders of magnitude greater than would be attainable with state-of-the-art electrical interconnects. The effort will address both development of an ultimately manufacturable and environmentally tolerant optical backplane, and the optical interface concepts required for practical board-to-backplane optical connection. The key functionalities, and compatibility with standard multiboard assembly practices will be demonstrated in a laboratory evaluation system.

Technical progress achieved during the current reporting period, and plans for the next reporting period, are summarized in the following sections.

2.0 Progress Summary.

2.1 AlGaAs Modulator Array Development. Task leader: Dr. Charles Sullivan

During this reporting period, limitations to our baseline approach to the design and fabrication of splitters and waveguide modulators have been identified, and solutions for overcoming these limitations have been identified and tested. These solutions include the use of multi-mode interference structures for splitting and routing a single input beam to the four modulator devices, and the use of an intentionally doped p-i-n modulator structure.

2.1.1. Identification of limitations of uniformity and producibility.

We have completed our second-pass and third-pass fabrication runs using our first mask set C5332. Results from these runs have allowed us to identify several key problems which will limit the producibility of the structures which currently comprise our baseline approach. The baseline structures consist of conventional cascaded 1x2 splitter designs to distribute a single input to an array of four modulators and undoped metal-semiconductor-metal (MSM) modulator structures. The problems identified include the presence of photocurrent induced by the propagating light, poor uniformity of breakdown voltage and leakage currents, high optical insertion loss and poor uniformity of optical throughput. These problems will be mitigated through the use of devices with a p-i-n doping profile and new multi-mode interference 1XN splitter designs reported below.

2.1.2. p-i-n Waveguide Modulator Results.

We have designed, fabricated, and tested p-i-n waveguides and waveguide modulators in the third reporting quarter of the OETC program. Straight singlemode p-i-n waveguides with a nominal channel width of 2.0 μm are found to have a measured modal attenuation of 3.0 ± 0.1 dB/cm at 830nm. This compares with 2.0 dB/cm modal attenuation for undoped structures, which implies a 1 dB/cm penalty for adding doping to the structure. Experiments are underway to further reduce the attenuation for the p-i-n structures to the 1-2 dB/cm range. Test results for Mach-Zehnder interferometers built from this p-i-n waveguide design give a voltage-length product ranging from 7 V-mm to about 15 V-mm, compared to about 55 V-mm for the simple metal-semiconductor-metal (MSM) interferometers previously built using unintentionally-doped materials. This represents an improvement in device efficiency of 4 to 8 times and can be largely attributed to the much improved overlap integral between the applied electric field and the modal field. Thus the slight increase in attenuation seems a reasonable price to pay for the greatly enhanced modulation efficiency. Undesired photo-induced currents are only 1-2 μA at 20 V. The present p-i-n modulator results were obtained using our standard Schottky metals design (not p-ohmics and n-ohmics) and without any electrical isolation between electrodes. Both of these shortcomings will be eliminated in the design and fabrication runs to be carried out in the next reporting period. The reduction in voltage length product is important for OETC since the total die length of the 1X4 waveguide modulator array can be kept below 1 cm with a drive voltage less than 5V. A smaller die size will probably result in higher yield and lower cost. Furthermore, it is possible that low-drive power operation can be obtained in device designs using single-sided drive, rather than the more complicated push-pull design originally planned for OETC.

2.1.3. Multi-mode Interference Splitter Results.

Based on recently reported results for multimode interference effect devices, we have designed, built and tested a variety of 1XN splitter devices. The splitter design and its incorporation and application to a four element modulator array is illustrated schematically in Figure 1.

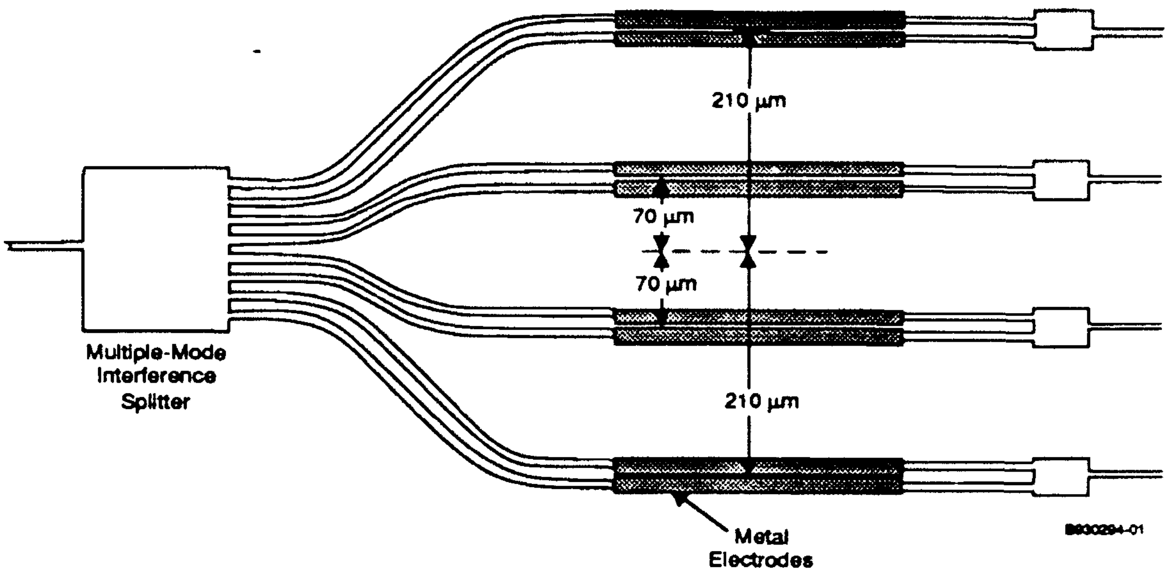

Figure 1. New Baseline Design for Four Element Modulator Array.

The length and width of the multimode region are chosen such that the desired number of channels appear at the output side. This splitter design approach is better suited to the deeply-etched fabrication process already developed at Honeywell in that all of the corners are 90° angles, rather than the very small angles (1°) required by the conventional splitter. Our preliminary data for the measured optical performance is illustrated in Figure 2.

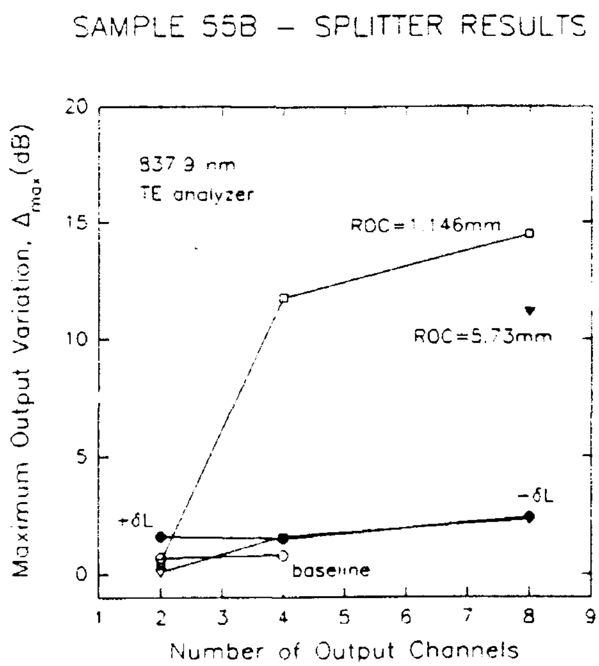

Figure 2 (a) Maximum Output Variation as Function of Number of Channels for MMI and Conventional Splitters.

SAMPLE 55B – SPLITTER RESULTS

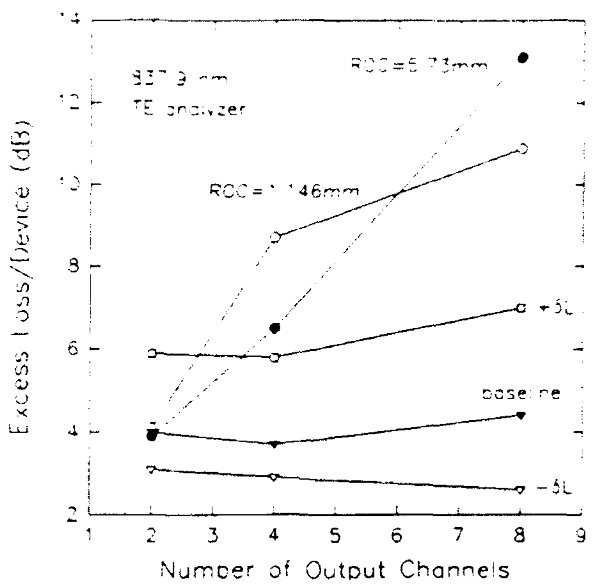

Figure 2 (b). Excess Loss Versus Number of Output Channels for Multi-Mode Interference Splitters (labelled baseline, +δL, -δL lengths) and conventional Splitters (labelled ROC (radius of curvature)).

The curves marked "baseline, +dL, and -dL" refer to the multi-mode interference designs and indicate the baseline length for the splitter region, and lengths larger and smaller than baseline by 20μm. The curves marked ROC refer to the conventional splitter designs with the radius of curvature (ROC) indicated. Figure 2(a) shows a very good uniformity of throughput lightwave power (initial results give a worst-case channel-to-channel difference of 1-2 dB) and Figure 2(b) indicates an excess insertion loss which is essentially independent of the number of output channels (4.4 ± 1.5 dB per device for the baseline design, exclusive of the intrinsic fanout loss). Even lower excess insertion loss (3dB) is measured for the "-dL" case, perhaps indicating that the finished dimensions of the "-dL" multi-mode interference splitter were better matched to the wavelength of the input light. The data shown in Figure 2 for the conventionally designed 1XN splitters based on cascaded 1X2s indicates that the insertion loss scales as the number of 1X2s in the path, with typical excess losses of about 4 dB per 1X2. In addition, the uniformity of output light from the channels in an array is much inferior to that for the multi-mode interference splitter. Since the insertion loss is related to device and circuit yield, we expect these new designs to have significantly improved yield over conventional designs. Measurements are continuing on these new device structures, particularly to assess the wavelength dependence of excess loss and output lightwave uniformity.

2.2 AlGaAs Modulator Array Packaging. Task leader: Mr. John Lehman

During the current reporting period we have begun to assemble optically packaged AlGaAs waveguide chips and are evaluating the optical coupling efficiency over a range of temperatures. The approach for coupling the light out of the AlGaAs waveguide into the multimode fiber (to MAC II connector) has been established. A third pass design of the ceramic optical packaging fixtures is completed and fabrication has started. More detailed descriptions of these activities follow.

Several "dummy" waveguide modulators were optically packaged by aligning a single-mode polarization maintaining fiber to the input of the chip using the baseline approach described in quarterly status report #2. As part of the evaluation of the packages, different adhesives were looked at. A desirable adhesive will have a low coefficient of thermal expansion (CTE), low shrinkage during cure, cures quickly and operates over a wide temperature range without losing strength. Temperature performance measurements of optically packaged assemblies were conducted to evaluate the stability of the singlemode fiber connection to the modulator. The packaged assembly was placed on a thermal-electric heater/cooler and the change in throughput power was recorded. The assumption is made that the change in throughput power is due to temperature induced optical misalignments. Figure 3 shows the relative change in optical coupling over a 115C temperature range.

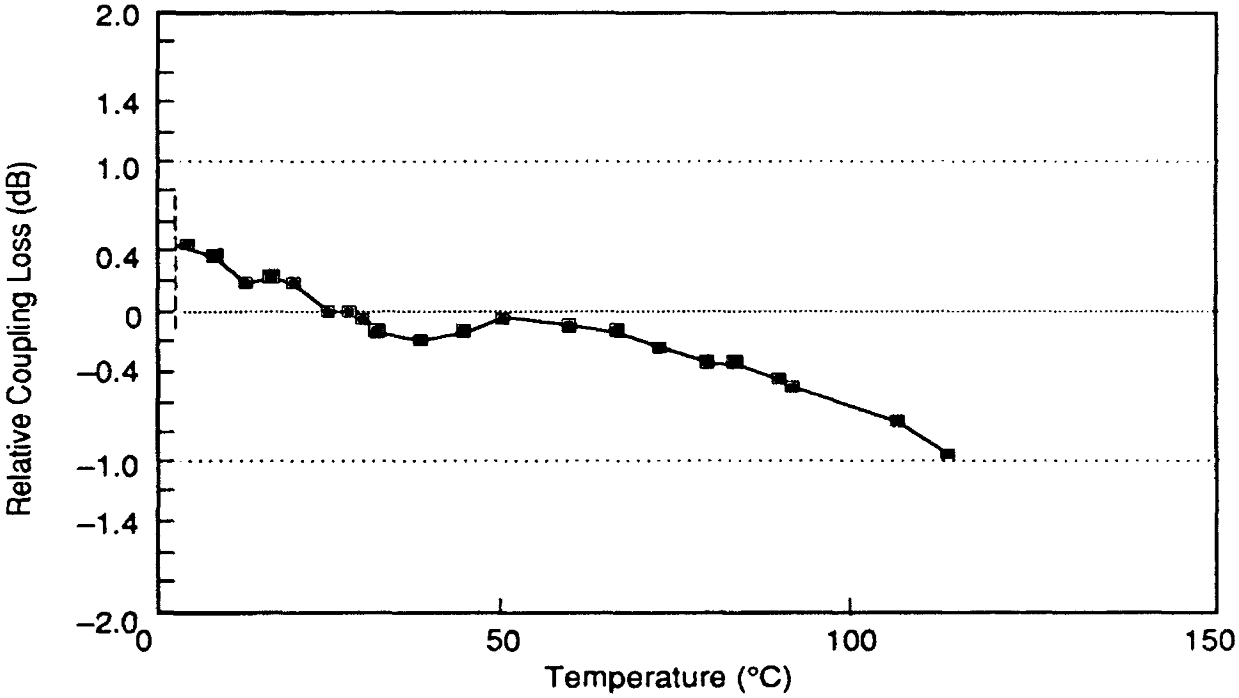

Figure 3. Temperature Dependence of the Single Mode Fiber Input to AiGaAs Waveguide Coupling.

The lower temperature limit is due to limitations in the present experimental setup. The upper temperature roll-off is due to the expansion of the epoxy. Our results to date were made using low shrinkage, moderate CTE epoxies. Other epoxies with lower CTE's are being evaluated as well. These epoxies exhibit good temperature stability over the range of interest for OETC but can take many hours to cure. During the next quarter we will be experimenting with thermoplastics which will have very quick cure times and will be reworkable. An added feature of the thermoplastic is that this material is mil-qualifiable.

The approach for coupling power out of the modulator waveguides into the SpecTran SG508 used in the fiber ribbon cable is to used lensed fibers set in a Si V-groove block. The v-groove block is the same as those used for the MAC II connectors with the 140µm pitch and is used primarily for optical alignment of the fibers to the waveguides. Active alignment would be used to maximize coupling before the fixture is set in place using epoxy. Pigtails from several modulator arrays will then be combined at a MAC II connector.

2.3. Polymer Backplane Development. Task leader: Dr. Julian Bristow

During the reporting period, we have focused our efforts on the demonstration of waveguides on practical board and backplane materials, and on characterization of an expanded beam interface which will form the basis of our board-to-backplane connector design.

2.3.1 Waveguide Fabrication on common board materials

We have selected glass: polyimide as our baseline backplane material. Typical multilayer boards may incorporate as many as thirty layers of glass: polyimide laminates, each with appropriate electrical traces defined, laminated together with a pre-impregnated glue under appropriate temperature and pressure. Our goal is to allow the optical waveguides to be incorporated with any layer of the laminate, using techniques, equipment, and ideally materials already encountered in the fabrication of purely electrical backplanes.

Glass: polyimide materials have rough surfaces. Examination of typical laminates reveals a periodic undulation in surface height, resulting from the weave of the glass fiber cloth in the laminate. Figure 4 illustrates the surface roughness of an "as received" glass:polyimide substrate from which the rolled copper coating has been chemically etched. Peak-to-peak roughness of 2.2 μm is observed. Note also the relatively high frequency components of the roughness. The rapid undulations in surface height are expected to cause significant optical loss, over and above the loss associated with absorption or scattering in a typical polymer waveguide system deposited on an optically smooth surface.

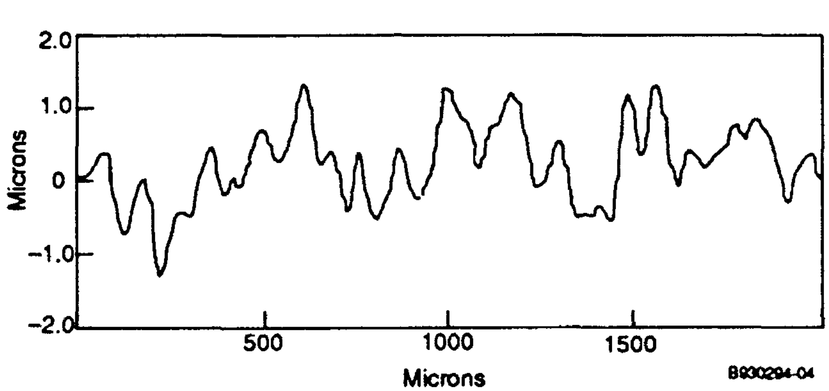

Figure 4. Surface Roughness of an As-Received Glass: Polyimide Substrate.

The optical loss resulting from incorporation of a multimode guide with a rough substrate depends on the periodicity of the surface height variation, their amplitude, and the characteristics of the unperturbed guide. Minimization of the optical loss requires planarization of the glass:polyimide material. The planarization process however must not render the board material incompatible with standard electrical board fabrication techniques. The two critical processes to be accommodated are the fabrication of the polyimide waveguides, and the incorporation of the optical waveguide layer into a multilayer laminate, a process which involves 100 - 200 psi of pressure, and temperatures up to 375°F. The planarizing layer may be followed directly by the optical waveguide layer, or by an optical buffer layer. The former option is preferable from the point of view of simplifying the fabrication process and therefore minimizing cost, whereas the latter will be required in situations in which the refractive index of the planarizing layer is too high with respect to the waveguide core material, or in which the bulk loss of the planarizing material would result in too high a loss for the composite waveguide.

During this reporting period we have characterized a number of planarizing polymers for compatibility with glass:polyimide board material and our baseline polyimide waveguides. Of the materials evaluated to data, the most promising is a Dow benzocyclobutene (BCB) material. This material was designed to have good planarization capabilities (91-99% degree of planarization) for electronic packaging applications. We have also determined the bulk refractive index at 830 nm wavelength, when used to fabricate thin (5-10) micron films. The refractive index was found to be approximately 1.57 at 830nm wavelength, offering the possibility for its use as a cladding layer for buried polymeric waveguides when used with polyimide guide cores. Propagation losses of 0.26 dB/cm have been measured for 10 μm planar films, indicating that the planarizing material can be used directly below the waveguide layer.

To evaluate the additional loss resulting from fabrication of polyimide waveguides on glass:polyimide circuit boards planarized in this manner, 4.0 μm thick films of polyimide were deposited on oxidized silicon wafers, and also on glass:polyimide substrates which had been planarized with DOW BCB (5 μm thickness). Figure 5 illustrates the resulting variation in surface height. Note that the peak-to-peak height variation has been reduced to less than 0.5 μm, while the high frequency variations have been eliminated. The loss of the planar guide was measured using standard prism coupling techniques. The additional loss associated with fabricating the waveguides on glass:polyimide substrates rather than the optically smooth oxidized silicon was determined to be 0.4+/-0.6 dB/cm. Further samples will be prepared to reduce the error in the experimental result, and also to investigate the effect of both thicker single coatings and repeated coatings of the same thickness of planarizing material.

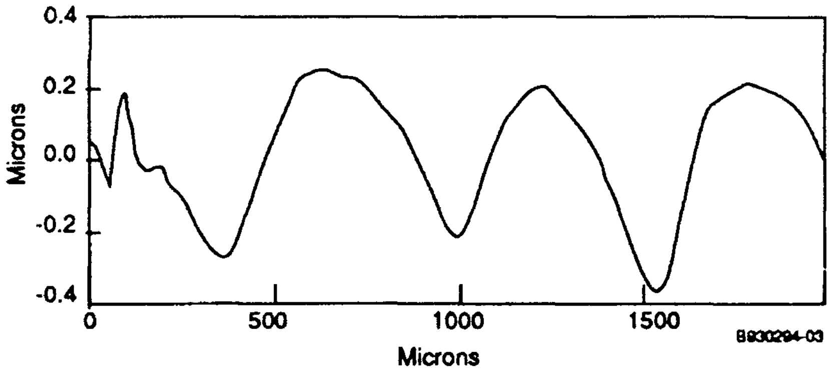

Figure 5. Surface Roughness of a Glass: Polyimide Substrate Planarized With a DOW BCB Polymer.

2.3.2 Board-to-backplane connector design

During this reporting period we have obtained initial results on the optical performance of the board to backplane connector. Our baseline design for the board-to-backplane connector employs a single gradient index lens pair connecting arrays of waveguides using expanded beam techniques. Figure 6 illustrates the experiment performed to evaluate connector performance limits. To evaluate the crosstalk characteristics of the gradient index lens used for the connector, a set of input guides and a separate set of output guides were interconnected using a conjugate pair of gradient index lenses of 0.19 pitch. The waveguide end faces are located at the focal plane of the lenses. The interface between the two lenses is therefore an expanded beam. Each point on the focal plane corresponds to a given angle in the expanded beam. Since each waveguide has a finite width and height, the output from each waveguide corresponds to a set of angles of expanded beams. The light from each waveguide is focused onto the input to the second set of waveguides, the input faces of which are located at the focal plane of the second lens. In a practical board to backplane connector, the 90-degree directional change would be effected by a micro-optical prism mounted between the board and backplane lens fixtures.

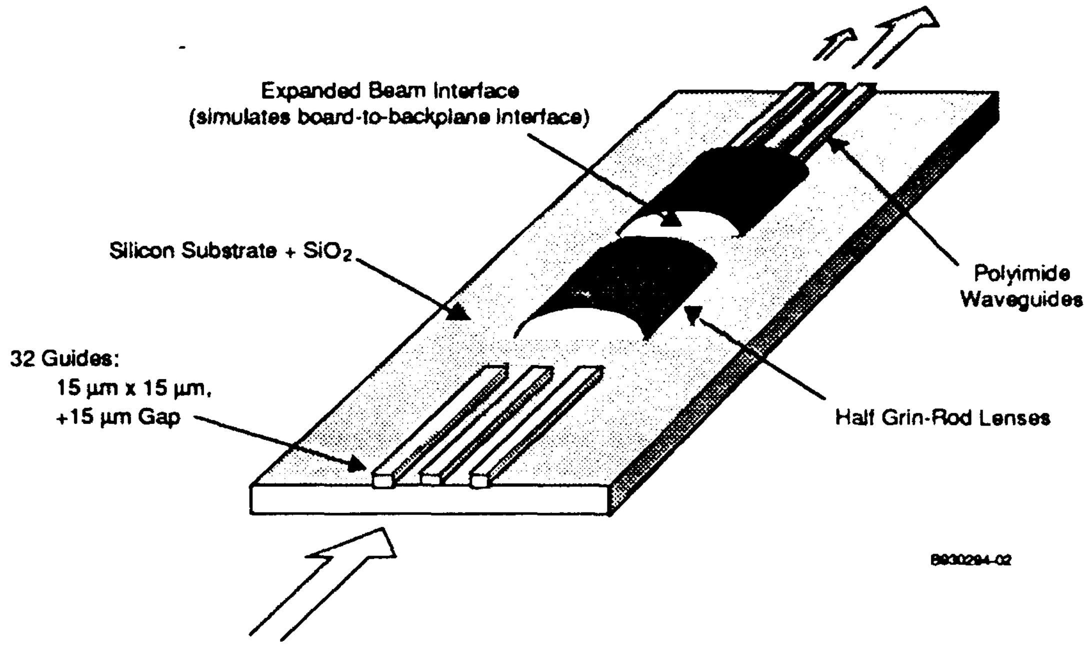

Figure 6. Illustration of the Experiment to Measure Expanded Beam Connextor Cross-Talk.

Registration features for the gradient index lenses were incorporated into the polyimide waveguide fabrication masks, allowing the lens fixtures to be located laterally without active alignment. This passive alignment feature will minimize the cost of incorporation of optical interconnects in practical backplane based systems.

The gradient index lenses are cut and polished to slightly more than half their original diameter so that the axis of the waveguide lies on the axis of the lens. Active monitoring of the lens polishing process is currently performed, however mounting of the lens in an abrasion resistant fixture will allow self-limiting polishing of the lenses for low cost production in the future.

Having mounted the half gradient index rod lens on the silicon substrate using the polymer alignment fixtures, the crosstalk was measured as a function of displacement from the axis, by measuring the output from channel n' and n+1' for input into channel n. Figure 7 shows the resulting crosstalk for the single lens pair. For the 3mm diameter lens, an optical crosstalk of better than -20 dB is maintained over a total distance of 1.8 mm. We note that the best crosstalk figure obtained for any lens pair to date has been -37dB. The waveguide dimensions for this experiment were 15µm x 15µm, with a 15µm gap, for a pitch of 30µm. This would imply that a single lens pair could be used to couple up to 60 waveguide channels from one board to another with better than 20 dB crosstalk with the stated dimensions, or that 45 guides of our target dimensions of 25µm x 25µm with a 15 µm gap could be used. Note that in a typical implementation, the optical signal would pass from the source board to the backplane, and thence to a second board, thus the optical crosstalk figure for a complete interconnect with two connectors would be -17dB, translating to an electrical crosstalk of -34dB, or 20mV crosstalk noise per 1 volt of signal.

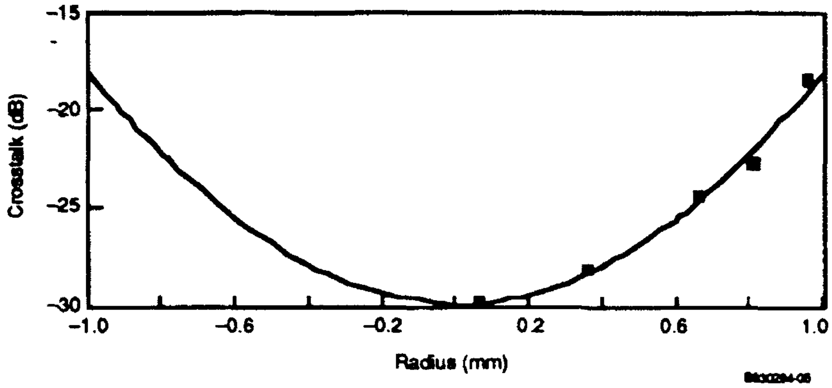

Figure 7. Results of Cross-Talk Measurements Between Neighboring Channels for the Expanded Beam Connector.

3.0. Fourth quarter plans.

3.1. AlGaAs Modulator Array Development.

We will design, build and test waveguide modulator arrays based on our recent successful results from the multimode interference effect devices. The baseline design will use only two masks for MSM devices, and a third mask will be used to provide electrical isolation in pin device structures. Electrical interconnections between the bonding/probing pads and the signal electrodes will rest on GaAs bridge structures rather than use polyimide planarization techniques. This approach will reduce the fabrication time by about 50% and possibly improve the device yield, with only a negligible cost in optical performance.

3.2. AlGaAs Modulator Array Packaging.

During the next reporting period we will assemble a complete optical package (i.e. single-mode input, multimode output) on the same submount and do a complete evaluation of coupling losses and the additional environmentally induced losses. Fabrication of the third design of ceramic submounts will be completed. These units will have internal heating resistors to allow us to work with thermoplastics and will also aid in curing of epoxies. We will also collaborate with Martin Marietta to define the approach for the electrical packaging of the modulators together with the driver chips they are fabricating.

3.3. Polymer Backplane Development.

During this quarter we plan to optimize the planarization process and demonstrate an integrated waveguide system comprising a glass: polyimide circuit board, planarizing/buffer layer, optical waveguide layer, and cladding, compatible with multilayer lamination procedures. We also plan to design the board to backplane lens mounting fixtures, and to fabricate initial connector fixtures to demonstrate key features of the board to backplane interface.

4.0. Summary.

Significant progress has been made in the current reporting period in addressing the issues of device uniformity, producibility and insensitivity to the thermal operating environment. The use of a doped p-i-n epitaxial structure significantly reduces the voltage-length product, and has the additional benefits of reducing the dc bias voltage which must be applied, reducing the leakage current, reducing the photo-induced conductivity, and improving the breakdown voltage uniformity across the wafer. The use of multimode interference splitter structures is much less sensitive to the details of the fabrication process, and results in significantly lower loss than conventional, cascaded 1x2 splitters and higher uniformity in the output channels from the splitter.

A thorough design and experimentation process in the area of packaging of the modulators with a single mode fiber input has resulted in the ability to vary the ambient temperature over a range in excess of 100 C, with less than 1 dB change in the optical coupling between fiber and waveguide.

The ability to planarize a standard glass: polyimide backplane has been demonstrated by the measurement of a significant reduction in the average peak to valley height, and a significant increase in the average period of surface modulation. The success of this planarization process has been confirmed by the fabrication of polyimide waveguides on top of the planarized boards with only 0.4 dB/cm excess insertion loss over waveguides fabricated on surfaces polished to an optically smooth finish. The ability to couple up to 60 polymer waveguide channels through a grin lens pair into a matching set of 60 channels has been demonstrated with crosstalk between neighboring channels less than -20dB.